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Three Decades of Very Long Baseline Interferometry Monitoring of the Parsec-Scale Jet in 3C 345

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Abstract. The 16$^{\rm th}$ magnitude quasar 3C 345 (redshift z=0.5928) shows structural and emission variability on parsec scales around a compact unresolved radio core. For the last three decades it has been closely monitored with very long baseline interferometry (VLBI), yielding a wealth of information about the physics of relativistic outflows and dynamics of the central regions in AGN. We present here preliminary results for the long-term jet evolution, based on the 15 GHz monitoring data collected by the MOJAVE survey and various other groups over the last ∼14 years and combined with data from earlier VLBI observations of 3C 345 which started in 1979. We discuss the trajectories, kinematics, and flux density evolution of enhanced emission regions embedded in the jet and present evidence for geometrical (e.g. precession) and physical (e.g. relativistic shocks and plasma instability) factors determining the morphology and dynamics of relativistic flows on parsec scales.

1. The Source

The 16$^{\rm th}$ magnitude quasar 3C 345 (redshift z=0.5928) has been observed at radio wavelengths for over 30 years, in particular with VLBI (cf., Biretta et al. (1986), Baath et al. (1992), Zensus et al. (1995), Unwin et al. (1997), Lobanov & Zensus (1999), Ros et al. (2000), Lobanov & Roland (2005)). The source still continues to be of special interest due to its complex, helical parsec-scale jet around a compact unresolved radio core and its pronounced multiwavelength variability. A likely 8-10 years periodicity of the high activity phases in 3C 345 has been identified (Lobanov & Zensus 1999). Measurements of nuclear opacity and magnetic field strength (Lobanov 1998) yield a total mass for the central engine of $(4.0 \pm 2.4) \cdot 10^9$ M$_\odot$. We have analyzed VLBI observations of the last three decades in order to understand the physics of the relativistic outflow and dynamics of central regions in 3C 345. Preliminary results of this analysis are presented here, focusing specifically on trajectories, kinematics, and flux density evolution of enhanced emission regions embedded in the jet.

2. Observations

We made use of a total of 201 observations (see Table 1) that included Very Long Baseline Array (VLBA) observations obtained from the NRAO Archive, observations by the MOJAVE survey, and published values pre-dating the VLBA

(before 1995)[1]. Archival VLBI observations were calibrated using NRAO's Astronomical Imaging Processing System (AIPS). The total intensity and polarization data was processed, with corrections applied for atmospheric opacity (if deemed necessary), Faraday rotation, and Earth orientation parameters used by the VLBA correlator. Fringe fitting was used to calibrate the observations for group and phase delays. The then calibrated visibility data was imaged using Caltech's Difmap (Shepherd et al. 1995). The source structure was modelfitted using circular Gaussian components. At the end, individual Gaussian components were cross-identified at different epochs in order to follow the evolution of individual bright features in the jet.

It should be noted that the physical nature of these features, also referred to as jet components, is still a matter of debate. Presently, the common viewpoint is that moving jet features are relativistic shocks in the jet plasma emitting optically thin synchrotron radiation.

Table 1. Overview of VLBI observations used in this work.

Time	# of epochs	Frequencies	Type
2009-	6+6+6	15,24,43 GHz	BS193, BS194 (VLBA)
2002-2009	12	15 GHz	MOJAVE Survey (VLBA)
1995-2009	61+7+7	15,22,43 GHz	archival re-reduced (VLBA)
1979-1995	48+48	1-15,22-100 GHz	published data[1]
1979-2009	Total: 201		

3. Results

3.1. Component C9

The VLBI data collected on the pc-scale jet in 3C 345 reveals 16 bright features (labeled C1-C16, with C1 being the oldest feature) that we are able to represent by circular Gaussian modelfits. Fits representing C1 were ignored in this analysis due to a lack of observations at $\geq$5 GHz as well as fits for C16, which appeared after 2007, were ignored. The left plot of Figure 1 shows the evolution of radial separation of one of the jet components (C9) from the stationary core of the jet. For observations other than at 15 GHz, a mean core-shift referenced to the 15 GHz VLBI core position (defining the core-shift at 15 GHz to be 0 mas) has been determined and applied, yielding an overall frequency-dependent position correction of $\Delta r\,(\nu) = (1.37 \cdot \nu(\mathrm{GHz})^{-1} - 0.058)$ mas. The notable gap between 2000 and 2002 is due to an emerging new jet feature causing substantial blending and making component identification problematic. The data from that period are ignored at the moment. The gaps 2005 - 2006 and 2007 - 2008 are due to a lack of usable VLBI observations in these periods. The plot shows a

[1] Unwin et al. (1983), Unwin & Wehrle (1992), Biretta et al. (1986), Zensus et al. (1995), Baath et al. (1992), Lobanov (1996), Krichbaum et al. (1993), Ros et al. (2000), Klare (2004)

possible acceleration phase before 1998 and a subsequent transition to a constant apparent speed. A linear fit to the observations around 1997 yields a time of zero separation from the core of 1995.95 ± 0.29. The proper radial motion for a distance of $r < 0.3$ mas from the core is 0.099 mas year^{-1} and for a distance $r > 0.3$ mas of 0.378 mas year^{-1}.

The 15 GHz flux density evolution of the component has a peak of (1.81 ± 0.11) Jy (Fig. 1:*right*). The time of the peak is 3.43 ± 0.31 years past the point of ejection. Analysis of the flux density evolution of all components at 15 GHz gives an average time of the peak after zero separation of ∼3.2 years.

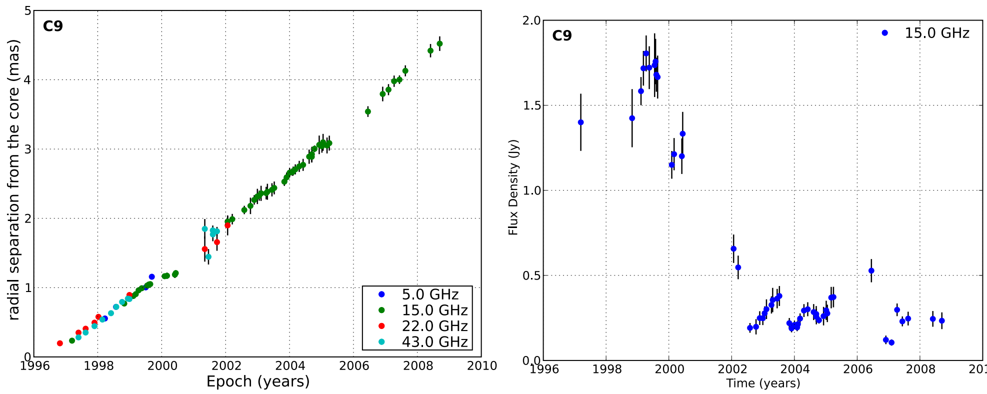

Figure 1. *Left:* Radial separation from the core plotted over time for the individual jet feature labeled C9. The gap between 2000 and 2002 is due to difficulties of component identifications that will be resolved in the future. *Right:* Flux density evolution of the jet feature C9 at 15 GHz for a period of 13 years.

3.2. Trajectories

Figure 2 shows the trajectories of all jet features. The jet is traced up to about 15 mas distance from the core. The measurements become more sparse at distances r>8 mas as a result of less frequent observations at frequencies ≤8 GHz.

The jet is initially directed westward, at a position angle of almost 90°. The individual jet features trace a common channel of ∼1 mas in width, within a distance of ∼5 mas from the core. Beyond this distance the jet sharply turns northwards.

This northward turning evolves in time. Earlier components were turning at around 3 mas, more recent features turn at 5 mas. Evidence for long-term changes are seen at shorter distances as well.

In Figure 3, the trajectories in the region up to 5 mas separation from the VLBI core are shown. It looks like subsequent features follow slightly different paths. The northward turning points evolve in a way that C8 follows C10, C7 and then C9. It looks like a wiggling of the jet turning point on smaller scales. A behavior like this is expected for a helical, precessing jet. This needs to be testedquantitativelyy in future work. The maximum relative core separation in declination varies from component to component. This is especially evident in the region up to 1.5 mas from the jet. C7 shows a maximum separation of

$\sim$0.1 mas, but C8 gets up to $\sim$0.2 mas. followed by C9 at $\sim$0.3 mas. After this, C10 as well as C11 come back to $\sim$0.05 mas. This behavior is curious and a precessing jet model will be tried in order to explain this as well.

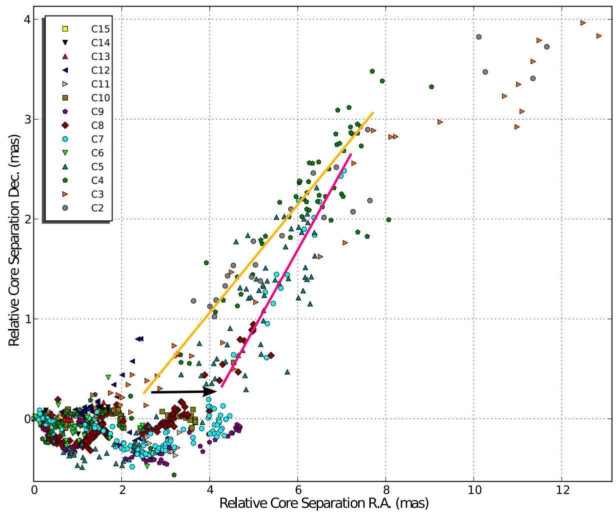

Figure 2. Trajectories of all jet features plotted on top of each other.

3.3. Evolution of the component ejection angle

The component position angles measured at 0.5 mas radial distance from the VLBI core at 15 GHz offer a different way to represent the previously described deviations from the 90° position angle (core separation in declination) in the trajectories of subsequent jet features C4-C15 (1983-2007), as shown in Figure 4. We see no clear periodic trends as has been claimed in the past. Lobanov & Roland (2005) and Klare et al. (2003) describe in their work a short-term periodicity of 8-10 years with an underlying long-term trend of 0.4-2.6° year^{-1}. We cannot confirm this here, but we see long-term variability as well as short term changes in the position angles since 2000. The reason these short term changes are not seen in earlier observations is due to the lower sensitivity and sampling of observations pre-dating the VLBA (before 1995). At that time only the brightest features were detectable. With recent, more sensitive and more frequent observations, we are able to see much more structure in the jet and are even able to see the bright edges of the jet. As stated above, we need to check whether the observed behavior can be brought into agreement with a precessing-helical jet model.

3.4. Apparent velocities

Apparent velocities $\beta_{\rm app}$ have been determined for all components. A proper motion of 1 mas year^{-1} is translated to a $\beta_{\rm app}$ of 19.7 h^{-1}c in concordance with the standard ΛCDM (H_0 = 70 km s^{-1} Mpc^{-1} and $\Omega_\Lambda = 0.72 = 1 - \Omega_M$, h is the dimensionless Hubble parameter). We have not been able to determine a common velocity for separations <0.7 mas; however we find an upper limit of $\beta_{\rm app}$ $\leq$2.25 h^{-1}c. For a separation >0.7 mas, we obtained a $\beta_{\rm app}$ $\approx$7.0 h^{-1}c

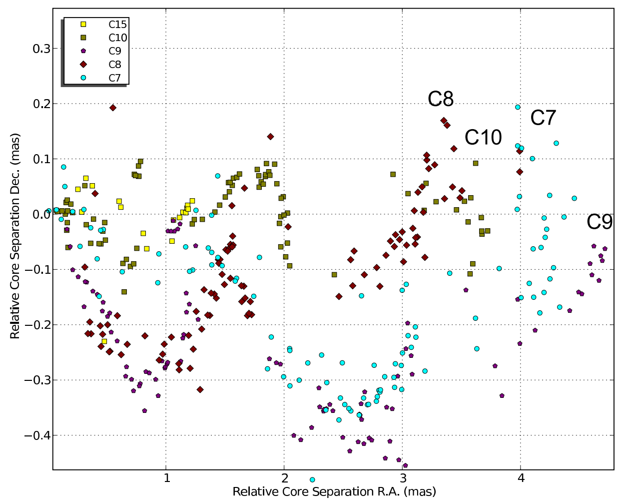

Figure 3. Close-up view of the trajectories for separations <5 mas.

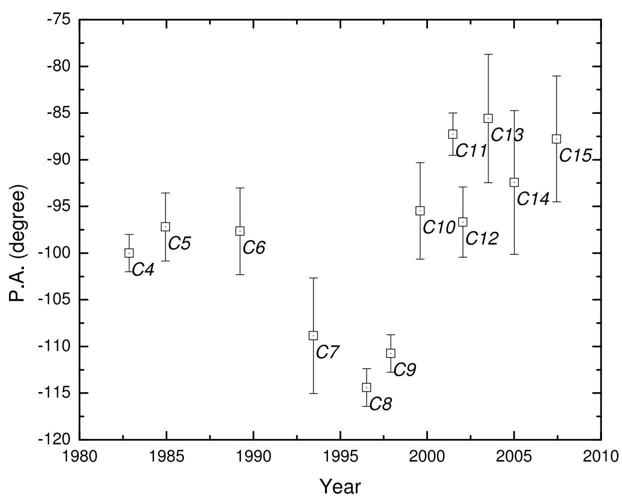

Figure 4. Plot of position angles for each jet feature at a separation of 0.5 mas from the core vs time.

for most of the components, with the exception of two features that show an apparent velocity of ≈9 $h^{-1}c$.

4. Summary & Outlook

3C 345 shows a complex jet morphology with many bright features observed by VLBI which have been traced for three decades now. We found a consistent superluminal motion of moving jet features at distances >0.7 mas and an apparent acceleration from smaller velocities at closer distances. We saw evidence for long- and short-term evolution in the jet trajectories of subsequent VLBI features as expected by a precessing jet with helical morphology.

We are going to expand this observational analysis to study spectral evolution as well as coreshifts. We are going to test various models in order to explain the underlying physics of the observed phenomena quantitatively.

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